CHAPTER 2

DWDM CONCEPTS

2.1 INTRODUCTION

Light frequencies are of the order of $10^{14}$ Hz. Fiber optic communication has provided us with high-speed communication with enormous bandwidth potential as described by Senior (2007). The performance of any communication system is limited by Signal-to-noise ratio (SNR) of the received signal. In the optical communication system also, the performance is limited by Optical Signal to Noise Ratio (OSNR) of the received optical signal.

![Figure 2.1 Structure of an Electromagnetic spectrum](image)

**Figure 2.1 Structure of an Electromagnetic spectrum**

Figure 2.1 shows an electromagnetic spectrum indicating the visible frequencies, UV and Infra-Red frequencies along with wavelengths. Optical fiber communication system uses three windows based at 850 nm, 1310 nm and 1550 nm. Among the three windows, the 1550 nm window which has
minimum attenuation is normally is used for Long-haul communication, as described by Decusatis and Carolyn (2007). Keiser (2008) has presented the complete list of advantages of an optical communication system.

G.652 fiber is the standard single-mode fiber (SMF) which was installed in 1980s and optimized in the 1310 nm range. G.653 fiber is the Dispersion shifted fiber (DSF) optimized at 1550 nm in 1990s. It is optimized in the sense that both attenuation and dispersion are minimum as discussed in Agrawal (2002). For minimizing the nonlinear effects, G.655 fiber which has non-zero dispersion at 1550 nm has been developed and used nowadays.

Shannon derived the celebrated formula for the capacity ‘C’ of the communication system as

\[ C = W \log_2 \left( 1 + \frac{P_o}{P_N} \right) \text{ bits/sec} \]  

(2.1)

where

- \( W \) is the channel bandwidth.
- \( P_o \) & \( P_N \) are the average optical signal power and noise power

As per Equation (2.1), the capacity is supposed to be increased, when the input optical power and hence OSNR is increased. However, beyond certain threshold of input optical power, the capacity starts decreasing because the fiber behaves in a nonlinear manner. Jau Tang (2006) described the nonlinear channel capacity and obtained the formula for the maximum Shannon capacity of a single mode fiber. The capacity depends on the dispersion of the fiber also.
2.2 TRAFFIC DEMAND

The exponential growth of Bandwidth-hungry Internet-based applications like Video-on-Demand (VoD), Games on-Demand (GoD), and Multimedia applications demand more capacity in existing fiber optical backbones. The Trends in Optical Networks like paving the way for increased capacity and more intelligence in optical networks are examined in the Literature (Erman 2001). Lots of 3G/4G wireless services are overloaded on the fiber optic backbones. The explosive growth of Internet is mentioned in a nutshell in his Guest Editorial by Cheung (2003).

A rough estimate of today’s traffic demand will be around 10 Tb/s, for supporting telephone traffic/video traffic and other multimedia data traffic. Currently available systems support only 0.8 Tb/s (80 channels x 10 Gb/s each). Now it has been upgraded to 3.2 Tb/s (80 channels x 40 Gb/s each) and also at the research level, it is 51.2 Tb/s (512 channels x 100Gb/s each). The above estimate is for a single strand of fiber.

![Diagram of a point-to-point optical communication system](image)

**Figure 2.2 Point-to-point optical communication system**

The recent rapid increase in the data traffic has led to the need for an ultra-high capacity transmission system. Whatever may be the attractive value-added and multimedia services being added to the wireless devices, ultimately they are putting burden on the Fiber optic backbones. In order to
meet the above traffic demand, passing single wavelength through a single fiber is not sufficient as shown in Figure 2.2. The scaling of optical communication for the next decade and beyond is illustrated by Tkach (2010).

![Graph showing Traffic Demand Vs System Capacity for four decades](image)

**Figure 2.3 Traffic Demand Vs System Capacity for four decades**


Figure 2.3 shows the crossing of demand and available capacity curves for North America. In India, there are only 1.33 crore Broadband Internet connections and so we have many unused fiber capacity. However, Indian Government approved a project for National Optical Fiber Network in Nov 2011 for Broadband Internet connectivity to all 2.5 Grama Panchayats at a cost of ₹ 20,000 crore. Hence the crossing point may occur after two or three years. The emerging broadband access networks in Korea is dealt in depth indicating the data traffic demand by Yong and Dongmyun (2003). Initially at point A, i.e in the year 1993, due to the introduction of DWDM, the system capacity (blue colour curve) is above the demand (red colour curve) and the situation remained constant until 2011. The deployment of bandwidth hungry applications such as High Definition Television (HDTV) in
access networks is well explained in the Literature Zhang and Nirwan (2009). Now due to the explosive growth of internet and multimedia based applications, the traffic in the OFC backbone is greater than the system capacity, as indicated by the cross over point at B.

2.3 THE FUTURE TRAFFIC DEMAND

Over the past 20 years principally enabled by Wavelength Division Multiplexing (WDM), fiber-optic transport capacities have been growing exponentially. As a result of world wide R&D, in the optical communications field, the capacity per fiber has increased at a rate of 100 every 10 years reaching 32 Terabits/sec in recent research demonstration as described in the literature Chraplyvy (2009).

Even though fiber could be considered as a bandwidth ocean, recent information-theoretic studies have concluded that the capacity of conventional fiber optic systems is not as limitless as had been thought. Scientists and Engineers are struggling to squeeze the last few doublings of capacity by implementing the complex modulation formats.

2.4 DIFFERENT WAYS OF IMPROVING THE CAPACITY

There are different ways of Improving the Capacity to cater to the traffic demand viz.,

- Space Division Multiplexing [SDM]
- Optical Time Division Multiplexing [OTDM]
- Wavelength Division Multiplexing [Coarse WDM & Dense WDM ]
2.4.1 SDM

In SDM, more fibers are to be installed. Sometimes a dark fiber (an unused fiber which is available in a fiber cable) can be lit or a new fiber could be installed. It is an expensive one.

2.4.2 OTDM

There are some limitations or bottlenecks in the electronic TDM. Upto 40 Gb/s could be electronically time division multiplexed and converted into an optical domain signal. Nowadays, a 100 Gb/s time division multiplexing is feasible. If we have to go for still higher data rate, Optical Time Division Multiplexing (OTDM) has to be used. Both Packet interleaved and bit interleaved OTDM are used. Still the equipments are costlier.

2.4.3 WDM

It is an easier way to increase the capacity. As shown in Figure 2.4, information is carried in any formats in individual channels (wavelengths) and they are merged or multiplexed into a single optical signal and then passed through a single fiber enhancing the overall capacity. Only a DWDM with optimized number of wavelengths (carriers) serves to cater this traffic.

![Figure 2.4 Point-to-point WDM optical communication system](image_url)
2.5 TYPES OF WDM

There are two types of Wavelength Division Multiplexing

- Coarse Wavelength Division Multiplexing (CWDM)
- Dense Wavelength Division Multiplexing (DWDM)

DWDM is characterized by high channel count greater than or equal to 32 and narrow channel spacing, whereas CWDM is characterized with low channel count and large channel spacing.

2.5.1 Coarse Wavelength Division Multiplexing (CWDM)

With a capacity greater than WDM and smaller than DWDM, CWDM allows a modest number of channels typically eight or less, to be stacked in the 1550 nm region of the fiber called the C-Band. To dramatically reduce cost, CWDM systems use uncooled lasers with a relaxed tolerance of ± 3 nm. CWDM uses a spacing of 20 nm, whereas DWDM systems use channel spacing as close to 0.4 nm. The wide spacing accommodates the uncooled laser wavelength drifts that occur as the ambient temperature varies. The total CWDM optical span systems use lasers that can have a bit rate of 2.5 Gb/s (OC-48/STM-16) and can multiplex up to 18 wavelengths. This provides a maximum of up to 45 Gb/s over a single fiber. The transmitting laser and receiving detector are typically integrated into a single assembly called a transceiver. The relaxed optical frequency stabilization requirements allow the associated costs of CWDM to approach those of non-WDM optical components. CWDM is also being used in cable television networks.
2.5.2 Dense Wavelength Division Multiplexing (DWDM)

Dense wavelength division multiplexing (DWDM) is an important innovation in optical networks. Figure 2.5 shows the evolution of DWDM right from 1980s to till date. Dense wavelength division multiplexing, refers originally to optical signals multiplexed within the 1550 nm band so as to leverage the capabilities of erbium doped fiber amplifiers (EDFAs), which are effective for wavelengths between approximately 1525–1565 nm (C band) or 1570–1610 nm (L band). EDFAs were originally developed to replace SONET/SDH optical-electrical-optical (OEO) regenerators, which they have made practically obsolete. EDFAs can amplify any optical signal in their operating range, regardless of the modulated bit rate. In terms of multi-wavelength signals, so long as the EDFA has enough pump energy available to it, it can amplify as many optical signals that can be multiplexed into its amplification band (though signal densities are limited by choice of modulation format). EDFAs therefore allow a single-channel optical link to be upgraded in bit rate by replacing only equipment at the ends of the link, while retaining the existing EDFA or series of EDFAs through a long haul route. Furthermore, single-wavelength links using EDFAs can similarly be upgraded to WDM links at reasonable cost. The EDFAs cost is thus leveraged across as many channels that can be multiplexed into the 1550 nm band.

Figure 2.5 Evolution of DWDM
2.6 BANDS IN DWDM

Different Bands in an Electromagnetic spectrum used for DWDM fiber optic communication system are shown in Table 2.1. The conventional band (C-band) is centered around 1550 nm and all other windows are named according to their location on the wavelength scale relative to the center wavelength.

Table 2.1 Optical Wavelength Bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Description</th>
<th>Wavelength range</th>
</tr>
</thead>
<tbody>
<tr>
<td>O band</td>
<td>Original</td>
<td>1260-1360 nm</td>
</tr>
<tr>
<td>E band</td>
<td>Extended</td>
<td>1360-1460 nm</td>
</tr>
<tr>
<td>S band</td>
<td>Short wavelengths</td>
<td>1460-1530 nm</td>
</tr>
<tr>
<td>C band</td>
<td>Conventional</td>
<td>1530-1565 nm</td>
</tr>
<tr>
<td>L band</td>
<td>Long wavelengths</td>
<td>1565-1625 nm</td>
</tr>
<tr>
<td>U band</td>
<td>Ultra long wavelengths</td>
<td>1625-1675 nm</td>
</tr>
</tbody>
</table>

Although fibers can support very high data rates, the associated electronic processing hardware will typically not be able to cope up with such high speeds. Light has an information-carrying capacity 10,000 times greater than the highest radio frequencies. Additional advantages of fiber over copper include the ability to carry signals over long distances, low error rates, immunity to electrical interference, security, and light weight. With an attenuation of less than 20 decibels per kilometer (dB/km), this purified glass fiber exceeded the threshold for making fiber optics a viable technology. AT & T first standardized transmission at DS3 speed (45 Mbps) for multimode fibers. Single-mode fibers were shown to be capable of transmission rates ten times that of the older type, as well as spans of 32 km.
Further developments in fiber optics are closely tied to the use of the specific regions on the optical spectrum where optical attenuation is low. These regions, called windows, lie between areas of high absorption. The earliest systems were developed to operate around 850 nm, the first window in silica-based optical fiber. A second window (S band), at 1310 nm, soon proved to be superior because of its lower attenuation, followed by a third window (C band) at 1550 nm with an even lower optical loss. Today, a fourth window (L band) near 1625 nm is under development and early deployment.

2.6.1 Wideband WDM

There is an exponential growth of Internet data traffic. It demands a huge bandwidth at the OFC backbone network. The ever-expanding growth of Internet and e-business have accelerated the data traffic loads in Metro / Access areas. The bandwidth hungry applications like Video-on-Demand [VoD], Games on Demand [GoD], 3G/4G Mobile services are overloading the Fiber-optic trunk lines. Although fibers can support very high data rates, the associated electronic processing hardware will not be able to cope up with such high speeds. Fiber optic cable can carry data at much higher data rates for greater distances. An enormous amount of bandwidth capacity is required to provide the services demanded by consumers. Everybody expect the network to be very fast i.e. High speed downloading, Broadband services, Video conferencing, etc. could be possible in a network, which necessitates a transmission rate of Peta bits per second (Pb/s) in a main trunk line and Tb/s for service provider(s) having more than ten thousand bandwidth hungry clients. So a high-capacity Wavelength Division Multiplexing (WDM) transmission systems are required in the Fiber optic backbone networks. The spacing in CWDM is shown in Figure 2.6.
2.6.2 Narrow Band WDM

Dense Wavelength Division Multiplexing (DWDM) is also a flexible technique, as the available capacity can be increased as and when required by installing additional terminal equipments, not disturbing the installed lengthy fiber optic cable. To meet this growing demand for bandwidth, a ultra-DWDM network has become the de-facto choice for the backbone network. Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called wideband WDM. The early 1990s saw a second generation of WDM, sometimes called narrowband WDM, in which two to eight channels were used. These channels were now spaced at an interval of about 400 GHz in the 1550-nm window. By the mid-1990s, Dense WDM (DWDM) systems were emerging with 16 to 40 channels and frequency spacing from 100 to 200 GHz. By the late 1990s, DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals. Nowadays, the frequency spacing would be even 6.25 GHz or a corresponding wavelength spacing of 0.05 nm. The spacing in DWDM is shown in Figure 2.7.

![Figure 2.6 Wavelength spacing in CWDM](image-url)
Figure 2.7 Wavelength spacing in DWDM

For achieving the data rate or capacity of 10 Tb/s, the factors influencing the capacity have been analyzed. Stimulated Raman Scattering [SRS] and Four Wave Mixing [FWM] and Dispersion are some of the bottlenecks (limiting factors) of capacity. In Dense Wavelength Division Multiplexing (DWDM) having N no. of wavelengths, each carrying the data rate of C bps in each channel. The total optical power density in a fiber gets increased due to which the fiber behaves in a non-linear manner. SBS limits the maximum input power per channel and hence maximum number of wavelengths. Dispersion limits the maximum bit rate of the individual channel. SRS produces unwanted crosstalk, among the channels. Individual wavelengths demand certain minimum optical power that is needed for maintaining the required BER (i.e not to exceed the set BER). By proper choice of the spectral width, more number of wavelengths could be added and the capacity could be increased. The spectral efficiency or capacity per unit bandwidth could be increased by setting the optimum amount of dispersion inside the fiber instead of zero dispersion. Thus the hurdles are overcome and thereby the capacity gets improved.

The increase in wavelength spacing increases SRS effect and the decrease in the spacing increases the FWM. Hence the spacing of adjacent wavelengths should be optimum. The component that limits the decreasing value of spacing is an optical filter at the de-multiplexer side. Large guard
band means filtering is easy without any ISI or fluctuations into the adjacent channel. However, overall occupied bandwidth covering the first channel to last channel gets increased.

2.7 RESTRICTION ON NUMBER OF WAVELENGTHS

Due to the ever-expanding Internet data traffic, telecommunication networks are witnessing a demand for high-speed data transfer. The increase in data transfer rate could be achieved either by increasing the base band transmission rate, and/or increasing the number of wavelengths in Ultra Dense Wavelength Division Multiplexing (U-DWDM) and/or increasing the Spectral Efficiency, in a fiber-optic backbone.

Overall capacity $C'$ of a DWDM network is given by Equation (2.2)

$$C' = C \times N$$

(2.2)

where

$C = \text{Capacity of the individual wavelengths}$

$N = \text{Number of wavelengths}$

By increasing the number of wavelengths to be transmitted through a single mode fiber (pair), the nonlinearities like FWM, SRS, SBS would also be increased, apart from the increase in the overall increase in the capacity. SBS sets the threshold maximum power for a single channel fiber-optic communication system, whereas SRS sets the limit of the transmitted power in a WDM signal. Also, every wavelengths need certain minimum optical input power for maintaining its own OSNR for easy detection. If $N$ increases, total power increases and if $N$ decreases, then power decreases.
But, allowable power per channel is less for high value of \( N \), which otherwise needs high total power. Hence we would have to use only optimum number of wavelengths.

As the number of wavelengths increased within a particular range \([\lambda_{\text{min}} \text{ to } \lambda_{\text{max}}]\), which may be C band alone (1525 nm to 1565 nm) or L band (1565 nm to 1625 nm), then allowable \( P_{\text{max}} \) per channel is decreased. It puts the restriction on \( N \). The applications of super DWDM technologies to terrestrial Terabit transmission systems are described in the literature Hiro Suzuki et al (2006).

For an ideal FOC link, Line width and Dispersion are to be set as zero. But in that case, FWM effect and SRS effect are more, as phase matching between the adjacent channels is more. The various combinations of these parameters are simulated in OPTSIM 5.0.

Now a days, 100 Gb/s optical networking components are commercially available. Components at 1 Tb/s are in the development stage in the research laboratories. The need for more capacity in existing networks is driven by the exponential growth of bandwidth-hungry internet-based applications. Optical networks are the only viable solution to this challenge.

International Telecommunication Union Telecommunication Standardization Sector (ITU-T) has standardized the minimum frequency spacing for DWDM to 12.5 GHz, and several WDM transmission experiments with a channel spacing of 25, 12.5, or 6.25 GHz have been reported. Optical Nonlinear effects, such as Stimulated Raman Scattering (SRS) and Four-Wave Mixing (FWM) are likely to impose severe restrictions on transmitter power, wavelength spacing and the number of wavelengths in DWDM. Tiwari et al (1999) and Agrawal (2001) have given excellent explanations regarding the fiber nonlinearities.
2.8 DESIGN PARAMETERS FOR DWDM TRANSMISSION

DWDM system is a transparent system and it is a bit-rate and modulation format-independent scheme. It can accept any combination of bit rates on the same fiber at the same time. DWDM increases the capacity of existing networks by transmitting many channels with certain minimum optical power per channel simultaneously on a single fiber optic strand. Hence the power density inside a core region of a fiber is more and the fiber will behave as a nonlinear channel. Channel count has grown from 4 to 128 (and still more) and channel spacing has shrunk from 500 GHz to 12.5 GHz (still less).

Transmission capacity \( C \) is the product of the bit rate \( B \) and the number of wavelengths \( N \) as given by Equation (2.3).

\[
C = B \times N \tag{2.3}
\]

The number of wavelengths \( N \) is shown as

\[
N = \frac{K}{d} = KD \tag{2.4}
\]

Here, \( K \) is the Optical signal bandwidth,

\( d \) is the channel spacing, and

\( D \) is the channel density which is the reciprocal of \( d \)

By substituting Equation (2.4) into Equation (2.3),

\[
C = B \times K \times D \tag{2.5}
\]

Equation (2.5) indicates three ways to increase the total transmission capacity:
- Increasing the bit rate in individual wavelengths, which needs more power/channel
- Expanding the optical signal bandwidth (C & L-Band).
- Decreasing the channel spacing, which necessitates less spectral width of the source.

Each method has its own advantages and disadvantages. For eg., keeping on increasing the bit rate is not possible beyond certain limit, normally 100 Gb/s because of electronic bottleneck. Similarly, the optical bandwidth could not be extended beyond the S,C and L bands, because of limitation in the optical amplification by EDFA. Also, the dumping of more and more channels within one or two particular optical bands by decreasing the channel spacing necessitates less spectral width of the source and sharp optical filters in optical demultiplexer.